CRYOGENIC INDUSTRIES

FROSTBYTE

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Dual-Fuel Engine Technology Review for Maritime Shipping

With every second that passes, the world is becoming a smaller place. The rapid advancement of technology and transportation has made it possible to access nearly seamlessly any part of the globe. As the world becomes more connected, whether it be for goods or people, the importance of transportation cannot be overlooked. Transportation has opened access to markets that were unreachable a century ago and will continue to be a growing part of society. The advances in transportation wouldn't be possible without corresponding advancements in fields like energy. Energy for transportation is delivered in many different forms but is rooted in the world of hydrocarbons and petroleum.

Transportation of goods and people annually consumes around 111 exajoules (105 quadrillion BTUs) of energy. Most of this energy is consumed in forms of petrol and diesel, each holding roughly 38% of the market share. Jet fuel accounts for roughly 11%, fuel oil roughly 8% and natural gas roughly 3%. By the year 2040, world transportation is projected to consume 158 exajoules (150 quadrillion BTUs) which is a 42% increase above today's figures. One of the fuels which will help power this growth is natural gas, which is projected to have an 11% market share in 2040. As of today, roughly 61% of transportation energy is used for the movement of people while the remaining 39% is used for the movement of goods.

World transportation sector delivered energy consumption by energy source, 2010-40

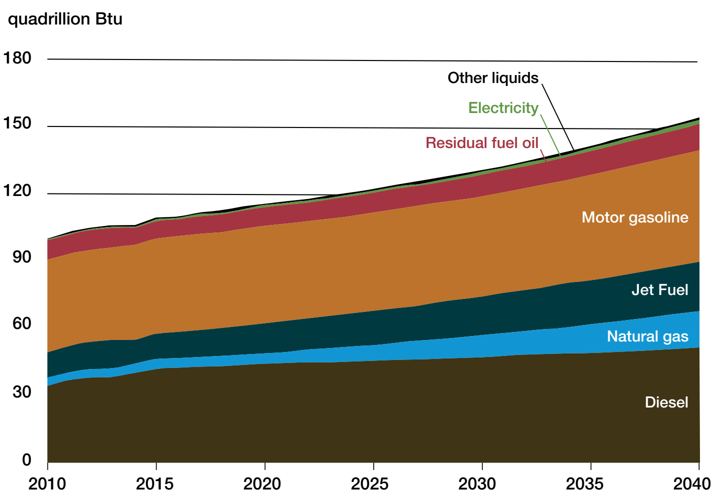

Figure 1. World transportation sector energy consumption by source

World transportation sector delivered energy consumption by freight modes, 2012 and 2040

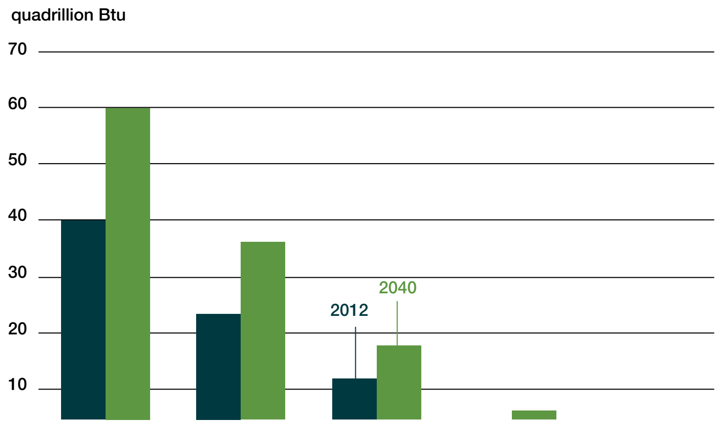

Figure 2. World transportation sector energy consumption by freight mode

When it comes to international movement for high volumes of goods, maritime shipping is the preferred choice. Nearly 13 exajoules (12 quadrillion BTUs) of energy, mostly fuel oil and diesel, is consumed annually by ships transporting goods. To put this in perspective, that's roughly equivalent to 100 billion US gallons of petrol annually. Even more astonishing, ships only account for 30% of the goods transportation energy consumption, with trucks consuming the majority at over 60%. By the year 2040, marine shipping will consume roughly 19 exajoules (18 quadrillion BTUs), which marks a 50% increase over today. Due to some recent regulatory changes regarding the pollution generated by ship engines, the shipbuilding industry has been compelled to explore some new emerging fuel alternatives to satisfy the growing goods transportation demand.

Solutions to Increasing Emissions Regulations

Ships typically use a variety of fuel oils with various viscosities, which are generally residual products of crude oil refining. The lighter distillate products end up as petrol, diesel and jet fuel which are a familiar part of everyday life. The problem with residual fuel oil is that it generates a variety of harmful pollutants when combusted. Residual fuel oil can contain large amounts sulphur which oxidizes to form SO_X compounds that produce acid rain. Due to the high combustion temperatures inside ordinary ship engines, nitrogen oxidizes to form NO_X compounds that also produce smog and acid rain. In addition CO_2 emissions are relatively high which adds greenhouse gas (GHG) to the atmosphere. Lastly, particulate matter (PM) emissions are quite high which reduces air quality and causes respiratory issues among people and animals.

The International Maritime Organization (IMO) made an environmentally conscious move in 1997 and again in 2008 to adopt a set of regulations called MARPOL Annex VI for SO_X and NO_X emission limits of ship engines. The IMO also began to outline certain areas, called emission control areas (ECAs) where special stringent emissions requirements would be enforced. Currently four such ECAs exist: Baltic Sea, North Sea, North American coastline and US Caribbean. More ECAs such as the Mediterranean are proposed but have not yet been adopted. In 2012, the SOx emissions global limit was reduced to 3.5% m/m. Pending a review in 2018, it may be dropped to 0.5% m/m which would come into force in 2020. Within the four existing ECAs starting in 2015, SO_X is limited to 0.1% m/m. For NO_X emissions, a global Tier II requirement came into force in 2011 but engine-makers were able to tune the engines to meet these requirements. Within the North American and US Caribbean ECAs, Tier III NO_X limitations came into effect at the beginning of 2016. The Tier III ECA NO_X requirement is only applicable to vessels with keels laid after January 1, 2016, whereas the SO_X ECA requirement is applicable to all vessels operating in the ECA.

A few methods exist to meet the SO_X ECA requirements. The first method is to use a low-sulphur fuel oil which is delivered pre-treated to the ship. Extra refining is needed using the hydrotreater, to remove the sulphur, therefore the cost of this fuel is higher than ordinary fuel oil. The second method is to use an exhaust gas scrubber which utilizes seawater or sodium hydroxide to chemically react with the SO_X and neutralize it. This means retrofitting the current exhaust system on the vessel with an aftermarket scrubber. The third method is to use LNG as fuel because the sulphur is nearly entirely removed as part of the liquefaction process of the gas. This option typically involves either an engine conversion or a completely new engine. Depending on the type of engine, a retrofit to gas injection might be possible. For new-build vessels, a variety of engines are available which can operate using natural gas as fuel. Depending on where the vessel is operating, a cost benefit analysis can be conducted to determine which method is the best. Recent low energy prices have made low-sulphur fuel oil more attractive than scrubbers, but the low-sulphur fuel availability is limited in some ports. The same availability concern exists with LNG, given that the supply and bunkering infrastructure is only now in its infancy.

The NO_X ECA requirements are slightly more difficult to meet, but there are a variety of methods available depending on the engine type. Given that the NO_X requirements are only applicable to new-builds from 2016 onward, retrofitting existing ships is not common. The first NO_X reduction method is using a selective catalytic reduction system (SCR) to chemically convert the NO_X to nitrogen and water. This system uses ammonia or urea which is injected into the exhaust gas and passed through a catalyst bed. This is a substantially bigger and more complex system than the catalytic converter on a car for instance. An SCR is useful in the instance where a new ship is being built to run on fuel oil, perhaps because LNG is not available or cost effective. The SCR does not remove SO_X, so either low-sulphur fuel oil or a scrubber would additionally be needed to meet those requirements. The second method for lowering NO_X emissions is to use LNG as a fuel. Two primary two-stroke low speed engines are available that can be fuelled by LNG. With the Wärtsilä X-DF engine, LNG as fuel alone will satisfy Tier III requirements. When using fuel oil in the X-DF, an exhaust gas recirculation (EGR) or SCR system is required to meet Tier III requirements. If there is an operating case for the vessel where LNG is not available, then the vessel will either need to be towed into the ECA or utilize an EGR or SCR. Regardless of fuel type, the MAN ME-GI engine does not meet Tier III requirements, and the engine requires an EGR or SCR to satisfy Tier III requirements. An EGR works by replacing O_2 in scavenge charge air with CO_2 from the exhaust which is recycled. CO_2 has a higher heat capacity which reduces peak cylinder temperatures. Also, with a reduction in O_2 concentration the combustion speed slows which reduces peak temperatures.

Other emissions from the ship engines can include PM, CO_2 and potentially methane. The IMO's MARPOL Annex VI does not specifically address PM emissions because they were shown to be linked to SOx emissions which are already regulated, hence no PM distinct regulation was needed. CO_2 emissions are addressed by an Energy Efficiency Design Index (EEDI) which is an equation-based index related to the amount of CO_2 generated per one tonne-mile of transport work. The index includes a reference number for ships built between 2013 and 2015 with expected CO_2 emission reductions for future ships. A 10% reduction is expected for ships built in phase 1 (2015 – 2020), 15 to 20% reduction for ships built in phase 2 (2020 – 2025) and a 30% reduction for ships built in phase 3 (2025 and

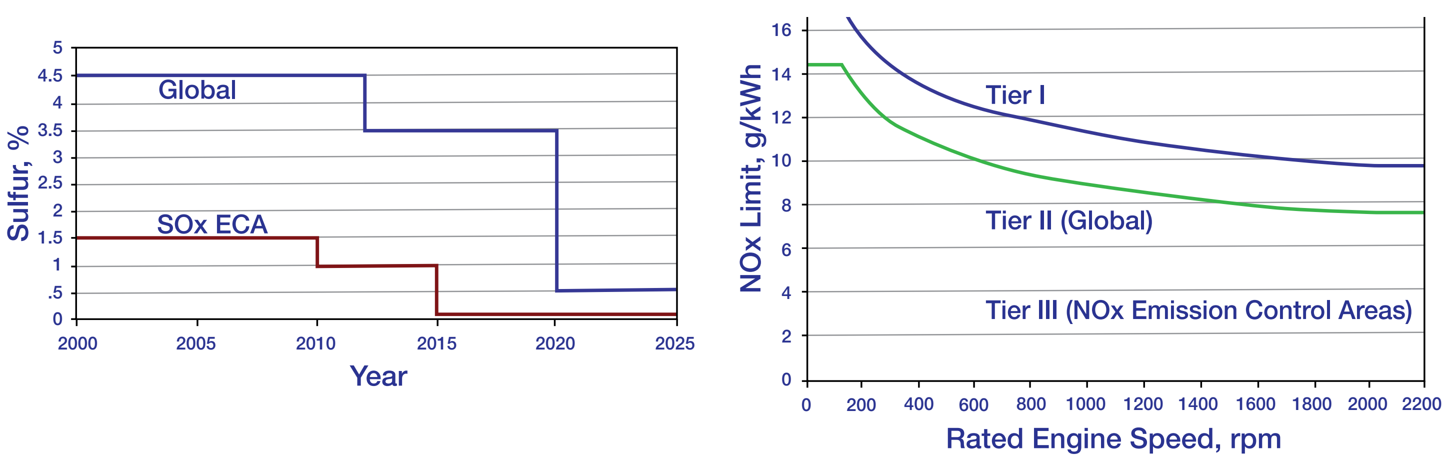

Figure 3. MARPOL Annex VI SO_x and NO_x emission requirements

beyond). The exact reduction values can be found in MARPOL Annex VI and are dependent on the type of the ship and deadweight. One last emission and likely most concerning is specific to Otto-cycle natural gas engines is 'methane slip'. This is simply incomplete combustion which results in methane being sent out with the exhaust gas. This is a significant concern because methane is roughly 34 times worse than CO_2 in global warming potential (GWP) over the span of 100 years. MARPOL Annex VI does not address methane emissions but future regulations will likely incorporate it given the severity of methane as a GHG. Even a small amount of methane slip can erase most of the GHG emission benefits that LNG offers.

Dual-Fuel Two-Stroke Engine Technology

The most common type of engine for large vessels is a two-stroke low speed engine. This type of engine works significantly different than what you'll find in most cars and trucks on the road today. The operation is quite simple due to a simultaneous intake and exhaust step. The charge air which is also called scavenge air is injected into the cylinder near the bottom of the piston stroke through a set of radial ports. Simultaneously, the exhaust exits out the top of the cylinder through a valve, in what is called uniflow scavenging. There is a slight offset between the two processes, meaning the exhaust valve opens slightly before scavenging begins and closes slightly before scavenging ends. The compression stroke upward closes the scavenge ports and the fuel is injected as the piston travels towards top dead center (TDC). When the piston reaches TDC, it begins the power stroke due to the ignition and combustion of the fuel. Near the bottom of the power stroke, the exhaust valve opens and the scavenge air ports are revealed again which completes the cycle. The power-to-weight ratio of a two-stroke low speed engine is higher because it has fewer moving parts than a four-stroke engine and can be directly coupled to the propeller shaft without a gearbox because the engine only operates up to around 100 RPM. The engine reliability is typically higher because of the lack of an intake valve and slower operation. The two-stroke engines can be easily identified by their tall height, which increases both the piston stroke length and efficiency during the power stroke.

MAN ME-GI

As previously mentioned, there are two engines utilizing two-stroke low speed technology which can be fuelled with natural gas. The first engine to market was the MAN ME-GI. The ME-GI engine sizes range anywhere from around 3000 kW to 80000 kW (4000 HP to 107000 HP). The basic principle of operation in the ME-GI is the Diesel cycle. This means that a pilot fuel oil spray of about 3% m/m is injected into the cylinder before the natural gas is injected, both immediately before TDC. The heat of compression creates cylinder temperatures high enough to auto-ignite the fuel oil, meaning no spark ignition is needed. The ME-GI can operate in a few different fuel modes including fuel oil-only mode, minimum-fuel oil mode and specified gas mode. In minimum-fuel oil mode, the engine will use 97% m/m gas for operation between 10% and 100% load. When the engine load drops below 10%, it switches to fuel oil only mode for combustion stability. In specified gas mode, the operator sets a fixed gas consumption rate and the control system substitutes the remainder of fuel required with fuel oil. The power rating and load response of the ME-GI remains the same whether operating on fuel oil or gas. In addition, the ME-GI can be fuelled with ethane and a separate variant called the ME-LGI can be fuelled with LPG or methanol.

The ME-GI has an efficiency of roughly 50% which is 3 to 8% higher fuel efficiency than its rivals, depending on engine load. Due to the late injection timing of the Diesel cycle, it does not suffer from misfiring and knocking issues which limits the operating window of Otto cycle engines. Given the resistance to knocking, the ME-GI is not affected by the methane number (MN) of the LNG fuel. Older LNG liquefiers usually produce rich LNG with a MN usually between 70 to 80, which requires derating of an Otto cycle engine due to an increased tendency to knock. With the ME-GI, the possibility exists to retrofit existing MAN ME-C two-stroke engines to ME-GI, giving owners the flexibility to adapt to LNG as fuel depending on fuel prices and availability. With regard to emissions, ECA SO_X requirements are achieved with LNG or low-sulphur fuel oil. Tier III NO_X requirements can be met with fuel oil and LNG but require an EGR or SCR. The Diesel cycle peak cylinder temperatures are roughly 300 – 500 °C warmer than the

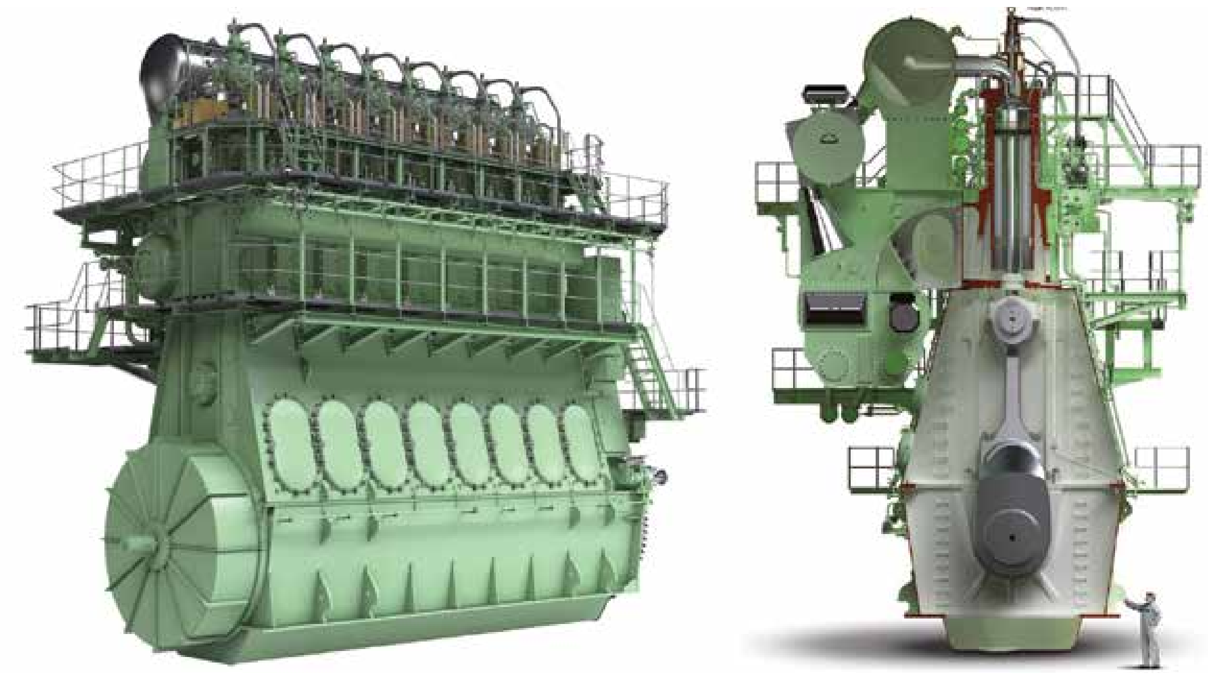

Figure 4. MAN ME-GI engine (Courtesy of MAN D&T)

Otto cycle, which makes the Diesel cycle more efficient but causes greater formation of NO_X. As previously mentioned, the EGR lowers these peak cylinder temperatures while the SCR chemically eliminates NO_X. For GHG emissions, CO_2 is reduced 25% when using LNG as fuel and methane slip is nearly zero, at less than 0.5 g/kWh. If paired with an EGR or SCR, the ME-GI is one of the most environmentally-friendly ship engines on the market.


Figure 5. Teekay's Creole Spirit LNG carrier powered by a MAN ME-GI engine (Courtesy of Teekay LNG Partners)

When using LNG as fuel in the ME-GI, the fuel gas system (FGS) requires high pressure reciprocating cryogenic pumps and vaporizers. This is necessary because the natural gas is being injected near TDC when cylinder pressures are near their peak. The typical injection pressure and temperature is around 300 barg and 45 °C. Sometimes a boil off gas (BOG) compressor is also included, which can fuel the engine or be paired with a reliquefaction system, depending on the vessel type and operational pattern. These auxiliary components that make up the ME-GI FGS consume roughly 0.5% of the engine's power. One of the major drawbacks of the ME-GI FGS is that it's quite a bit more expensive than the X-DF FGS, when excluding LNG fuel tank costs. The higher CAPEX is offset though by a lower OPEX with the ME-GIs better fuel efficiency. The payback time is dependent on the cost of fuel, which at the moment is very low and making for longer payback periods. This is putting direct pressure on the FGS cost as suppliers look to cut costs while maintaining reliability.

Wärtsilä X-DF

In late 2013, Wärtsilä released the X-DF engine. Prior to the release, most of the Wärtsilä development was focused on smaller gas-fuelled four-stroke medium and high speed engines that are used with smaller vessels like ferries, tug boats and small tankers. The X-DF engine sizes range from 7000 kW to 80000 kW (9400 HP to 107000 HP). The basic principle of operation in the X-DF is the Otto cycle. Gas is injected into the cylinder part way through the compression stroke, after scavenging has been completed. Pilot fuel oil of 1% m/m is injected right before TDC, which auto-ignites upon injection (due to the heat of compression of the pre-mixed air and gas). The X-DF can operate in fuel oil-only mode and a gas mode with 99% m/m gas throughout the entire load range. Development is still on-going for a mixed mode which is similar to the specified gas mode for the ME-GI. Power output is slightly derated and load ramping is required when in gas-mode compared to fuel oil-only mode. This usually means a slightly larger engine will be required and maneuvering can be difficult with load ramping.

The X-DF has an efficiency of roughly 47% depending on engine load, which is slightly behind the ME-GI but higher than other four-stroke dual-fuel engines. With the Otto cycle, knocking risk is always present, so the LNG fuel MN is very important and must be maintained over 80. In addition, the charge air temperature must be maintained below 50 °C; otherwise the engine power must be derated. With regard to emissions, ECA SO_X requirements are achieved with LNG or low-sulphur fuel oil. Tier III NO_X requirements are met in gas mode but not in fuel oil mode, so an EGR or SCR might be required if gas is not available in the ECA. For GHG emissions, CO_2 is reduced 25% when using LNG as fuel but methane slip is between 3 – 4 g/kWh. This means in gas mode the GWP is only reduced around 10% while the ME-GI engine has a GWP reduction of over 20%.

The LNG FGS for the X-DF requires low pressure fuel compared to higher pressure (300 barg) for the ME-GI engine, because it is an Otto cycle engine. The injection of the gas takes place only partway during the compression stroke at pressures of only 16 barg. Rather than using a high pressure reciprocating cryogenic pump, a standalone submerged centrifugal pump in the LNG fuel tank can be used. This reduces the maintenance required, as centrifugal pumps have a longer service life. If a BOG compressor is included, a variety of types are available (including centrifugal, screw and piston) giving the owner more options to choose from. The ME-GI and X-DF are roughly the same cost for the same engine size, so no CAPEX benefit is gained either way, but the X-DF might require a bigger engine size due to derating. In addition, the LNG fuel tanks might need to be up to 10% bigger due to the lower fuel efficiency of the X-DF. The LNG fuel tanks are typically the highest CAPEX item in the FGS, except with LNG carriers which use the cargo tanks as fuel tanks. When fuel prices increase, OPEX will begin to hinder the X-DFs CAPEX benefit.

Summary

Each engine has particular advantages which might be attractive to an owner depending on the type of vessel and operating pattern. Fuel cost, fuel availability and regulatory requirements will continue to be the drivers for owners to adopt or convert to new fuels. The LNG bunkering and liquefier networks are continuing to develop for widespread adoption, but the technology is already established and available on the market. LNG carriers have found the adoption much easier because cargo loading serves the purpose of bunkering and they are always assured to be calling at LNG terminals, guaranteeing fuel availability. With the persisting low fuel prices and sluggish shipping activity, older, less fuel efficient ships are more attractive than they were just a few years ago. Hidden shipping capacity exists due to ships intentionally slowing their speed, called slow steaming, inhibiting the demand for new ships. If the emissions regulations continue to push lower and new ECAs are adopted, an artificial boost might be created. The next decade in shipping will certainly be worth keeping any eye on.

For further information , go to www.Cryoquip.com.

"G-Type Engine Notches Up 1500 Orders" (2016, September 14). Retrieved from http://dieselturbo.man.eu/press-media/news-overview/details/2016/09/14/